UV Emission In Coma Supercluster

A study to investigate the role of environments on the behaviour of star forming galaxies.

Devika.S

A dissertation submitted for the partial fulfilment of BS-MS dual degree in Science.

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Certificate Of Examination

This is to certify that the dissertation titled "**UV Emission In Coma Supercluster**" submitted by Ms. Devika.S (Reg. No. MS12065) for the partial ful-filment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Prof. Jasjeet Singh Bagla	Dr. Satyajit Jena	Dr Smriti Mahajan (supervisor)

Dated: April 21 2017

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Smriti Mahajan at the Indian Institute of Science Education and Research Mohali.
This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Devika.S
MS12065
Dated: April 21, 2017

In my capacity as the supervisor of the candidate's project work, I certify that the above statement by the candidate is true to the best of my knowledge.

Dr. Smriti Mahajan
(Thesis Supervisor)

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Abstract

We examine the effect of environment on star forming galaxies across the Coma supercluster. Coma supercluster comprises two rich clusters of galaxies separated by 30 h^{-1}Mpc with a filament of galaxies crossing them. We analyse UV imaging from the Galaxy Evolution Explorer *(GALEX)* and optical spectroscopic and imaging data from the Sloan Digital Sky Survey (SDSS) to investigate the link between large-scale environment and various properties like broadband colour, morphology, star formation (SF) etc. for the galaxies residing in the Coma supercluster. We statistically examine the environmental dependence on galaxy properties by employing KS test for 1) all galaxies in an environment and 2) dwarfs and giants in an environment. KS test for all galaxies in different environments indicates that colour, morphology and SF activity of galaxies are environment dependant. KS test shows that some properties of dwarfs and giants have no environment dependence. Mainly current SF activity (EW (Hα)) of dwarfs in filament and field regions are found to be similar although their recent SF activity is different. KS tests also imply that dwarfs in these region have same morphology, but different colour. Similar behaviour is observed for giants in these regions.

Chapter 1

Introduction

Coma supercluster is one of the nearest superclusters located at a distance of $100h^{-1}$ Mpc from us [Chincarini and Rood, 1976, Gregory and Thompson, 1978]. Coma supercluster consists of two rich clusters Abell 1367 and Abell 1656 (Coma cluster) which are in turn connected by a filament of galaxies. In this thesis we study the environmental dependence of galaxy properties using SDSS and *GALEX* data. The Coma supercluster provides the opportunity to study galaxies in different environments at the same redshift.

Literature shows that galaxy properties such as morphology, star formation rate (SFR) are influenced by the environment they reside in. Environment is defined in terms of either surface or volume galaxy density [Tanaka et al., 2004a]. [Dressler, 1980] and [Whitmore et al., 1993] established the morphology-density relation which states that ellipticals and lenticulars are found in the high density cluster environments while the spirals and irregulars in low density regions. The SFR of galaxies in high dense environments seems to be suppressed as compared with the field [Tanaka et al., 2004b].
Several mechanisms were proposed to explain the observed environmental dependence of galaxy properties. For e.g., ram pressure stripping is found to be effective in high density cluster region [Gunn and Gott III, 1972, Abadi et al., 1999, Quilis et al., 2000] while in groups low velocity galaxy-galaxy interaction between galaxies is found to be more effective. The difficult part involved in the study of the environmental dependence of galaxy properties is that the correlation exists among the various galaxy properties itself. Therefore several studies were carried out to check the environmental dependence of galaxy properties when some parameters are fixed. One such study is done by [Park et al., 2007] who showed

that for a given morphology and luminosity other galaxy properties seem to be nearly independent of local density. [Skibba et al., 2009] showed that galaxy colour is environment dependant when morphology is fixed while morphology and environment are weakly correlated when colour is fixed which is found to be in agreement with [Deng and Zou, 2009] and [Deng et al., 2009]. [Skibba et al., 2009] claimed that the observed morphology-density relation is due to the colour-density relation. [Deng et al., 2010] studied the role of mass in the environmental dependence of galaxy properties by classifying galaxies into high stellar mass (HSM) and low stellar mass (LSM) at a stellar mass of $3\times10^{10}M_{\odot}$ and found that the mass is not fundamental in the observed correlation between galaxy properties and environment.

In the next section, we briefly discuss the different types of galaxies and their properties (Section 1.1) Finally, we detail the goals and the layout of the rest of this thesis (Section 1.2).

1.1 Classification of galaxies

The only information we can receive from a celestial object is in the form of light. Till 1940s observations were carried out in optical wavelength only. With the development in technology, present day observations can span the entire electromagnetic spectrum from the ground as well as space. One can use light to measure all parameters such as distance, mass, SF activity, colour, temperature ...etc. of any astronomical object.

Edwin P Hubble pioneered morphological classification of galaxies [Hubble, 1926]. He classified galaxies into four types: ellipticals, lenticulars, spirals and irregulars. Hubble defined morphology from the relative proportions of the two major structural parts of the galaxy, namely the bulge and the disk. The bulge is generally made up of relatively old and evolved stars which are characterised by red optical colour, and is shaped like an ellipsoid with various degree of flattening and oblateness (ellipsoid with no flattening and oblateness is a sphere). In general, the bulge contains no appreciable amount of dust and gas and therefore has very little star formation. The disk is composed of a mixture of old and young stars, gas and dust, and it is the site of active star formation. It is generally bluer than the bulge.

Elliptical galaxies consist only of the bulge component and have no disk. Spirals are of two types, normal and barred. Barred spirals are the ones with bar-like structure in the centre. Irregular galaxies generally do not have bulge, disk and the spiral arms but they tend to resemble spiral ones in terms of their colour, SF activity..,etc.

On the basis of their broadband colour galaxies are classified into red and blue. Red colour corresponds to passive evolution. Most of such galaxies are found to have either elliptical or lenticular morphology. Blue colour implies active SF and such galaies are morphologically spirals, irregulars and ellipticals as well.

There is another category of galaxies based on their mass; dwarfs and giants. As the name suggests giants are the massive galaxies while dwarfs are of low mass. Even though dwarfs are most abundant type of galaxies in the universe, they are hard to detect due to their low luminosity. We adopt the classification criteria from [Blanton et al., 2001, Mahajan et al., 2010] to classify our galaxy sample into dwarfs (z>15) and giants (z<14.5).

1.2 Plan for the thesis

In this thesis, we address the role of environment on galaxy evolution. In section 2 we discuss the data sample obtained from SDSS DR12 and *GALEX* DR6/7. In section 3 we discuss the methods adopted to partition the Coma supercluster. In section 4 we discuss the properties of galaxies in the Coma supercluster. In section 5 we discuss, how the properties mentioned in section 4 vary with different environments in Coma supercluster?

Chapter 2

Observational Data

2.1 Introduction

In this chapter we describe the data set that has been used for this thesis. We give a brief overview of Sloan Digital Sky Survey (SDSS) in section 2.2 and Galaxy Evolution Explorer (*GALEX*) in section 2.3.

2.2 SDSS survey

SDSS is the optical spectroscopic and imaging survey. SDSS has imaged more than one-third of the sky (shown in fig 2.1), and it has concentrated on the northern and southern Galactic caps which are above and below the plane of the Galaxy and has created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars. SDSS has completed three generation of surveys namely SDSS-I (1998-2005), SDSS-II (2005-2008), SDSS-III (2008-2014) and the SDSS-IV (2014-2020) which is currently on-going. In this thesis, DR12 which is the final data release of SDSS-III has been used.

The SDSS uses a dedicated 2.5-meter wide-field telescope at Apache Point Observatory, New Mexico (Gunn et al. 2006), instrumented with a sequence of sophisticated imagers and spectrographs. Optical fibres of $3''$ diameter is used for the spectroscopic observation. SDSS carry out its observations simultaneously in five bands namely *u, g, r, i* and *z* with an effective wavelength of 3543, 4770, 6231, 7625, and 9134 A^o respectively.

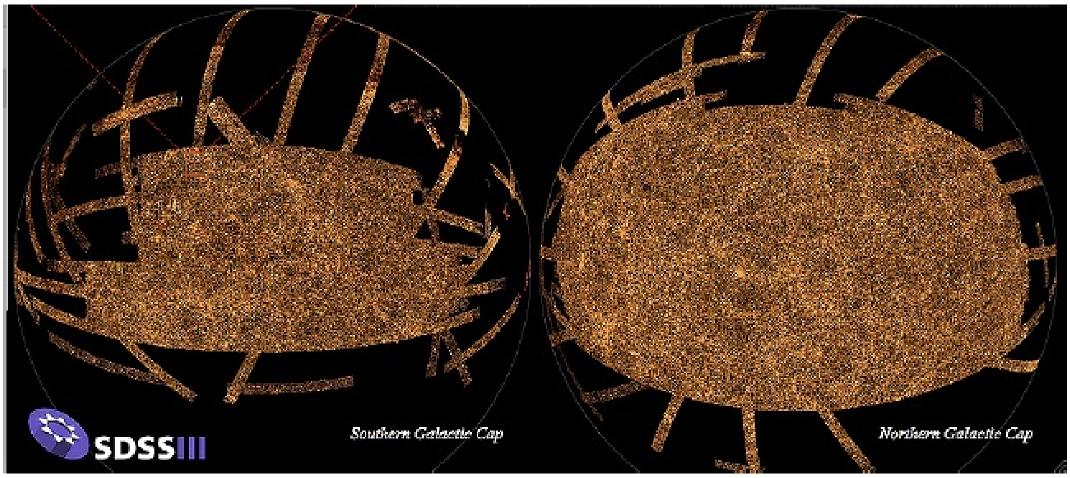

Figure 2.1: The area imaged by SDSS I,II and III (*Credit: M. Blanton and the SDSS-III collaboration)*

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2.3 *GALEX* Survey

GALEX is an orbiting UV space telescope launched by NASA on April 28th 2003. Since *GALEX* instruments are designed in such a way to look at the very faint objects in the sky, its telescope is always pointed away from the Earth and sun. Due to its high sensitivity *GALEX* cannot look at stars that our naked eye can. *GALEX* has done its wide field (1.2^o diameter) imaging in 2 passbands; Far-UV (*FUV*, 1344-1786 A^o) and Near UV (*NUV*, 1771-2831 A^o). The *GALEX* survey includes (Martin et. al 2005): 1) All Sky Imaging Survey (AIS, m$_{AB}$=20.5), 2) Medium Imaging Survey of 1000 deg^2 (MIS, m$_{AB}$=23), 3) Deep Imaging Survey of 100 deg^2 (DIS, m$_{AB}$=25), 4) Nearby Galaxy Survey (NGS) and Guest Investigator Programmes (GIPs).

2.4 Optical Data

We select the galaxies in the Coma supercluster from the SDSS spectroscopic database, requiring the member galaxies to be within 170$^\circ \leq RA \leq 200^\circ$, 17$^\circ \leq Dec \leq 33^\circ$ and 0.013$\leq$ z $\leq$ 0.033 on the sky [Mahajan et al., 2010]. All such galaxies are brighter than SDSS magnitude *r*=17.77 which is the ccompleteness limit for the SDSS spectroscopic catalogue. Thus the optical catalogue contains a total of 4,280 galaxies.

2.5 UV Data

UV data of galaxies belonging to Coma supercluster is obtained from the *GALEX* database by applying the same position criteria. The UV catalogue contains a total of 3,38,788 galaxies.

2.6 Matching the optical and UV sources

The optical and UV catalogue of the Coma supercluster are matched using an astronomical software called TOPCAT. We choose the nearest UV counterparts within $4''$ of each optical source. 477 optical sources were found to be multiply matched to a total of 1,032 UV sources within the matching radius of $4''$.

2.6.1 Multiple Matches

Multiple matches means a given optical source is matched to more than one UV source. Such UV sources are considered as duplicates if they lie within 2.5 arcsec of each other (Bianchi et.al 2011). If two GALEX sources were within this distance but had the same photoextractid (i.e., they are both from the same observation), they were both considered unique. Otherwise, they were assumed to be multiple observations of the same source.
In case of multiple observations of the same source, the unique source was assumed to be be the one with the longest NUV exposure time. And if the NUV exposure time come out to be equal for two such sources then unique source is considered to be the one closer to the field centre (i.e. the source with the smallest fov_radius, [Bianchi, 2011]).

After sorting out multiple matches, our final dataset contains 2,469 galaxies uniquely matched to SDSS sources. The next step is to calculate the distance and magnitude of each galaxy in the catalogue. The cosmological parameters we use in this thesis are Ω_Λ=0.7, Ω_M=0.3 and H_o=70 $\text{Kms}^{-1}\text{Mpc}^{-1}$ for calculating the luminosity distance (d_L) using the formula:

$$d_L = \frac{2c}{H_o}(1 + z - \sqrt{1+z}) \tag{2.1}$$

z = redshift
c = speed of light

Then we find the distance modulus (μ) from the distance calculated and used it to calculate the absolute magnitude of galaxy.

$$\begin{aligned} \mu &= 5log(d_L) - 5 \\ &= m - M - k_{corr} - A \end{aligned} \tag{2.2}$$

$$M = m - \mu - K_{corr} - A \tag{2.3}$$

m = apparent magnitude
M = absolute magnitude
K_{corr} = k correction
A = extinction

2.6.2 Extinction

The light we receive from a galaxy is subjected to absorption and scattering by dust on its way to Earth which makes the objects dimmer than they really are. This is referred to as extinction. Dust grains along the line of sight have size comparable to the wavelength of blue light. Hence the light reached on Earth is removed from the blue light and thus making the objects more redder than they really are. This is termed as interstellar reddening (reddening of the starlight). Therefore, more dust along the line of sight higher will be the reddening and extinction.

Degree of reddening, E(B-V), is defined as the difference between the observed colour, $(B-V)_m$, and intrinsic color, $(B-V)_o$, of the object.

$$E(B-V) = (B-V)_m - (B-V)_o \tag{2.4}$$

Extinction of a passband (A_λ) is estimated from the reddening in B-V colour, and the associated conversions [Bianchi, 2011, Stoughton et al., 2002] are shown in table 2.1.

In the SDSS database extinction corrected magnitudes are available while in the GALEX database E(B-V) data is available from which the A_{FUV} and A_{NUV} are calculated and are substituted in (2.3) to obtain extinction corrected absolute magnitude.

band	A_λ/E(B-V)
FUV	8.06
NUV	7.95
u	5.155
g	3.793
r	2.751
i	2.086
z	1.479

Table 2.1: conversion factor used to calculate the extinction in a a passband [Bianchi, 2011, Stoughton et al., 2002]

2.6.3 k-correction

Since the Universe is expanding, the celestial objects are either moving away from us or moving towards us. As a result, the light emitted is either redshifted or blueshifted. If an object is moving away from us then its light has to travel more distance which results an increase in wavelength and is termed as redshift (shifting of spectral line to higher wavelength). Similarly if an object is moving towards us then it has to travel shorter distance, making its spectrum shifted towards low wavelength which is termed as blueshift. The consequence is that apparent flux we measure in a passband, say R, corresponds to an emitted bandpass, say Q. The observed and emitted-frame bandpass has different shapes and positions in frequency space which has to be taken into account while calculating the absolute magnitude and has to be corrected. The term relating here the emitted and the observed bandpass is referred to as k-correction which is calculated using TOPCAT based on the algorithm by [Chilingarian et al., 2010, Chilingarian and Zolotukhin, 2012].

Chapter 3

Partitioning of Coma supercluster

3.1 Galaxy disribution

A supercluster means cluster of galaxy clusters. The coma supercluster contains two galaxy clusters A1367 and A1656. The sky plots of Coma supercluster are shown in the following figures. Fig 3.1 shows the spatial distribution of galaxies in the Coma supercluster having emission in the SDSS passbands (the details of SDSS passbands are given in section 2.2). To the fig 3.1, a third dimension 'distance' of the galaxies (redshift) is added and is shown in fig 3.2. Then we looked at which all galaxies in the Coma supercluster have emission in both optical (SDSS passbands) and UV (*FUV and NUV*) region of the electromagnetic spectrum (fig 3.3). From figure 3.2, it can be seen that most of the galaxies as well as two galaxy clusters of the Coma supercluster lie in the redshift range 0.02-0.025.

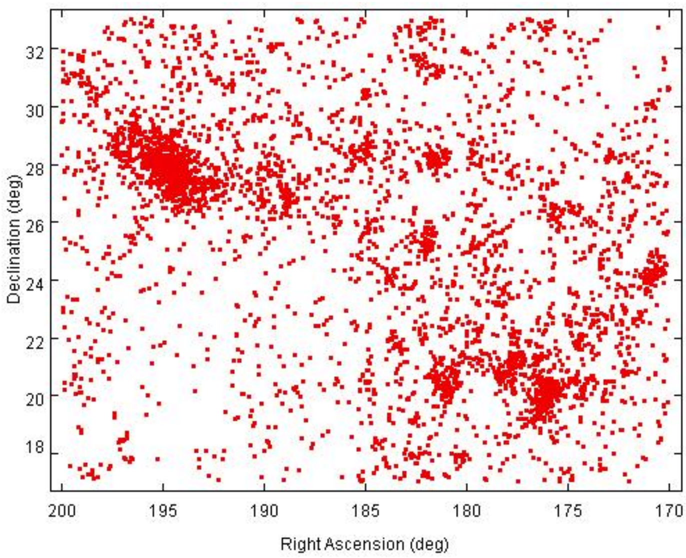

Figure 3.1: The spatial distribution of optically selected galaxies in the Coma supercluster

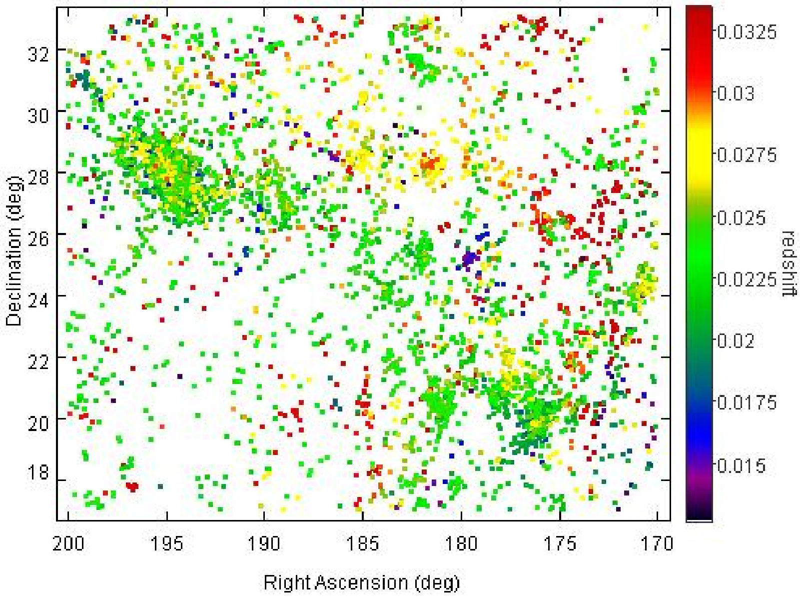

Figure 3.2: The spatial distribution of optically selected galaxies in the Coma supercluster along with the redshift data which is color coded here.

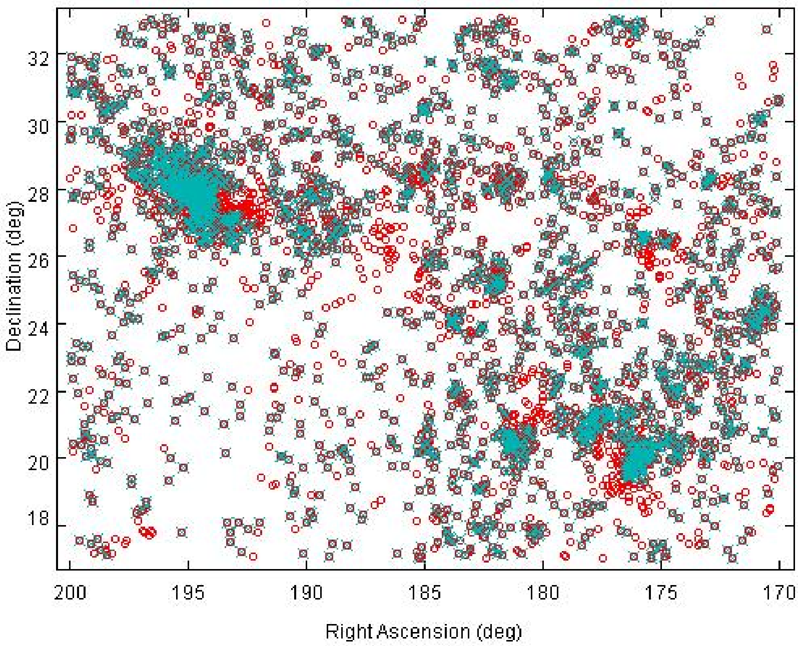

Figure 3.3: The open circles (red) indicate galaxies having emission in optical region while cross marks (blue), in UV region.

Table 3.1: Parameters for cluster region

Parameters	A1367	A1656
r_{200} (h^{-1}Mpc)	1.18	1.5
cz (Km/s)	6495	6973
velocity dispersion (Km/s)	745	957

3.2 Different environments in Coma supercluster

Environment of a galaxy is defined by the number density of galaxies in a given region. High density galaxy environments are the cluster regions which contains $\geq$100 galaxies. If galaxy number of galaxies in a region is between 10-100 in a given region, it is called as groups. Other than these an environment that is specific for a supercluster is the filament of galaxies. Galaxies which are not part of any of these mentioned environments are termed as field galaxies. Studying Coma supercluster offers an opportunity to study all these different kind of environments and thus understanding the galaxy evolution. In the previous section we have seen the spatial distribution of galaxies in the Coma supercluster. In this section we will partition the Coma supercluster into different environments.

We defined three environments in the Coma supercluster: 1) cluster (0-r_{200}), 3) filament and 4) field. The filament is the region that extends from r_{200} of A1367 to r_{200} of A1656 and the field refers to the region that is not part of any of these 3 environments. The parameters to define the cluster region are taken from [Rines et al., 2003] which is shown in table 3.1 We define the filament region as a prolate spheroid [Porter et al., 2008] with the two centres of cluster A1367 and A1656 as the end points, the distance between them being the major axis and 3.6 h^{-1}MPc being the semi-minor axis. The length of semi-minor axis is defined arbitrarily by looking at the spread of filament region for different values starting from 6 h^{-1}MPc, the value adopted by [Porter et al., 2008]. Different environments in the Coma supercluster are shown in fig 3.4.

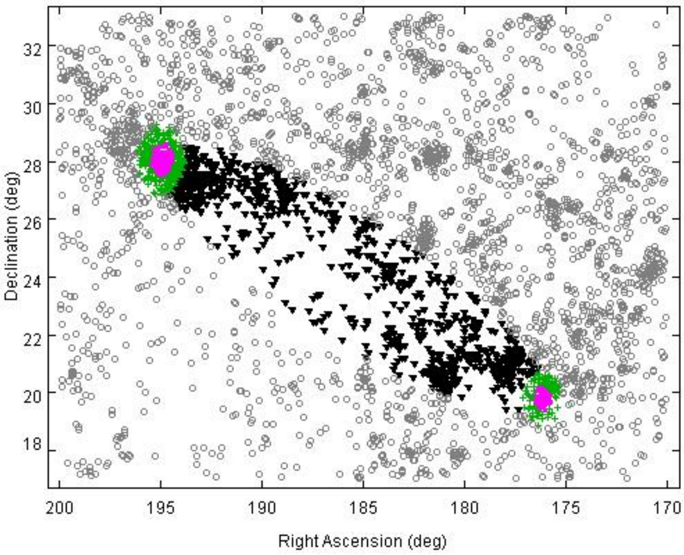

Figure 3.4: Different environments in Coma supercluster. The closed circles (pink) denotes the 0-$0.5r_{200}$, plus mark (green) denotes the $0.5r_{200}$-r_{200}, triangle (black) denotes the filament region and open circles (grey) denote the field.

Chapter 4

Analysis I: Properties of galaxies in the Coma supercluster

We created a catalogue of galaxies in the Coma supercluster having emission in SDSS passbands. From this optical catalogue, a subset is defined which contains only those galaxies that have emission in the *GALEX FUV* and *NUV* bands. The higher sensitivity of *GALEX* towards recent SF resulted in a greater separation between red and blue sequence in *NUV-r* vs *r* plot (fig 4.2) when compared with optical colour magnitude diagrams (fig 4.1).
We looked at various galaxy properties such as colour, morphology, mass, recent SF and current SF from the observables *NUV-r*, concentration index (CI), z-band magnitude, *FUV-NUV* and Hα-EW respectively. In this chapter we discuss the overall behaviour of galaxies in the Coma supercluster irrespective of their environment.

4.1 Colour

NUV-r distribution of galaxies (UV selected sample) in the Coma supercluster is shown in fig 4.3. Major fraction of galaxies belong to blue sequence as we expected. Since we deal with only those galaxies having the SF in a timescale of $<$ 1Gyr in UV data we looked at the *'u-r'* distribution (shown in fig 4.4) of galaxies in the optically selected sample to cross-check the fraction of blue and red galaxies. Even though *'u-r'* distribution of optically selected sample is bimodal, fraction of blue and red population seems to be similar which is contrary to the *NUV-r* and *u-r* distribution (fig 4.5, similar to *NUV-r* distribution) of UV selected sample. We conclude that our Coma supercluster contains both red and blue population, the fraction of which is almost similar and comparable.

From the *NUV-r vs r* plot (fig 4.2) and *NUV-r* distribution, we defined galaxies with *NUV-r* < 4.4 as blue galaxies and one with NUV-r > 4.4 as red galaxies. Similarly for optically selected galaxies, one with *u-r* < 1.83 as blue galaxy and one with *u-r* > 1.83 as red galaxy.

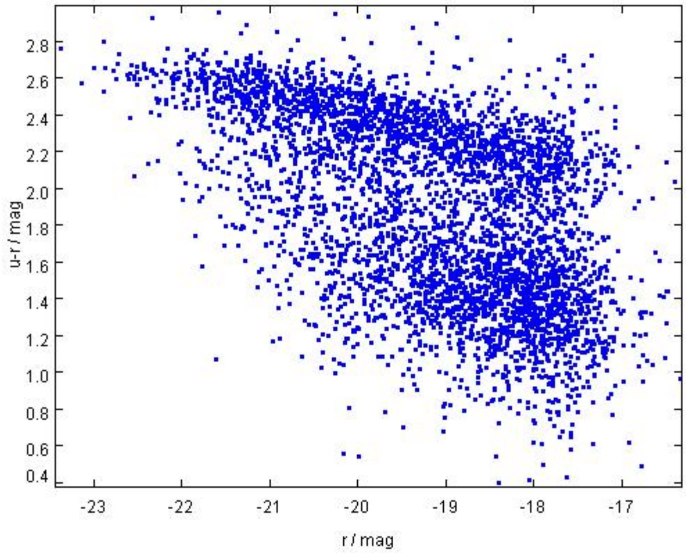

Figure 4.1: Optical colour magnitude plot between *u-r* colour and *r* magnitude

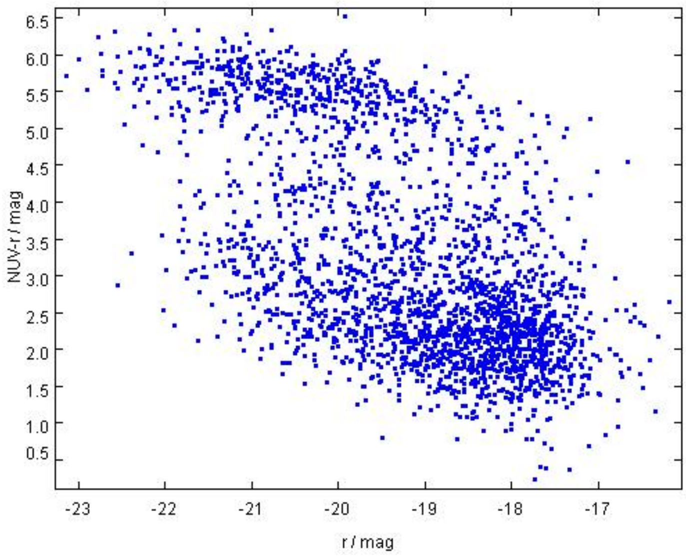

Figure 4.2: Colour magnitude plot between *NUV-r* colour and *r* magnitude.

4.2 Morphology

The concentration index (CI) is defined as the ratio of the radii containing 90% and 50% of the Petrosian r-band galaxy light. petroR90_r and petroR50_r data are available in SDSS database from which concentration index (CI) is defined and its distribution for both UV

Table 4.1: Fraction of spirals and ellipticals in UV and optical dataset

optiically selected		
morphology	number of galaxies	fraction
Spirals (Sb, Sc) and Irregulars (Irr)	2471	58%
Ellipticals and lenticulars (S0)	1809	42%
UV selected		
Spirals (Sb, Sc) and Irregulars (Irr)	1555	63%
Ellipticals and lenticulars (S0)	914	37%

and optical selected sample is shown in figure 4.6 and 4.7 respectively. Both distributions are unimodal in nature with roughly same mean, 2.535 for UV and 2.565 for optically selected sample. We adopted CI=2.6 as the morphology separator [Strateva et al., 2001]. CI<2.6 indicates spirals and irregular morphology while CI>2.6 indicates ellipticals and lenticulars. We calculated the fraction of different morphologies present in Coma supercluster which is given in table 4.1. From table 4.1, it can be seen that that major fraction of galaxies in Coma supercluster is of spirals and irregular morphology. Also majority of star forming galaxies are found to be of spiral and irregular types, only $< 40\%$ is ellipticals and lenticulars.

4.3 Mass

The emission from galaxies are observed at various wavelengths, and from those measurements, either the star formation rate (SFR) of galaxies or their integrated stellar masses are calculated. A galaxy's mass and the light emitted is highly related i.e. low mass galaxies (dwarfs) are less luminuous ones whereas bright galaxies are of massive types. The conversions from light to mass are derived or calibrated using stellar population synthesis models. We adopted galaxies with $z > 15$ as low mass ones (dwarfs) and $z < 14.5$ as massive ones (giants, [Blanton et al., 2001, Mahajan et al., 2010]). 64% of the galaxies in Coma supercluster are found to be as dwarfs whereas 26% are found to be as giants.

Table 4.2: Fraction of different types of galaxies in Coma supercluster

parameters		fraction (%)
colour	red	25
	blue	**75**
morphology	E, S0	37
	S, Irr	**63**
mass	giants	26
	dwarfs	**64**
SF	EW=0	5
	0<EW<4	22
	EW>4	**73**

4.4 Star formation (SF)

The star forming activity of galaxies is shown in fig 4.8. Majority of them (73%) are found to have current (< 1Myr) star formation (EW (Hα) > 4). Next we checked the correlation among these galaxy properties.

4.5 correlation among galaxy properties

The fraction of different types of galaxies present in Coma supercluster are shown in table 4.2.

- 73% of galaxies found to have significant SF. (EW (Hα) > 4, fig 4.8). We checked the colour, morphology and mass of these star forming galaxies.
- 98% of such star forming galaxies are found to be blue galaxies i.e. *NUV-r*<4.4 (fig 4.9).
- 79% of star forming galaxies are found to have *z*>15, i.e. dwarfs (fig 4.10.).
- 79% of star forming galaxies are found to be of spiral and irregular morphology, i.e. CI<2.6 (fig 4.11.).
- Altogether 64.79% of star forming galaxies are found to be low mass spirals with blue colour.

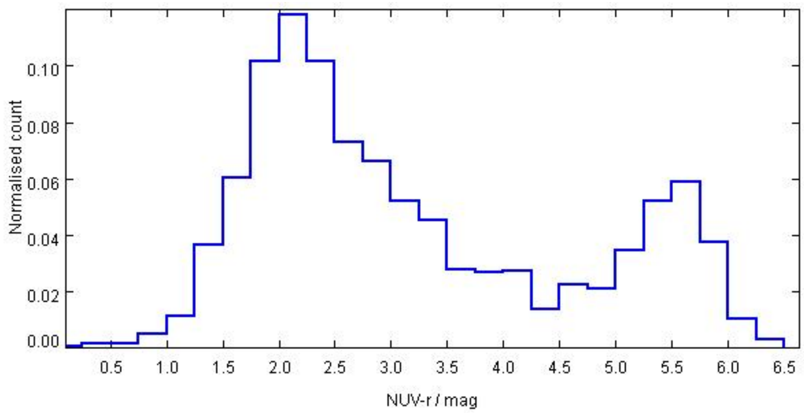

Figure 4.3: The bimodal distribution of NUV-r colour for UV selected galaxies indicates the existence of two type of galaxy population in Coma supercluster, 1) galaxies with low *NUV-r* value (blue galaxies) and 2) galaxies with high *NUV-r* value (red galaxies)

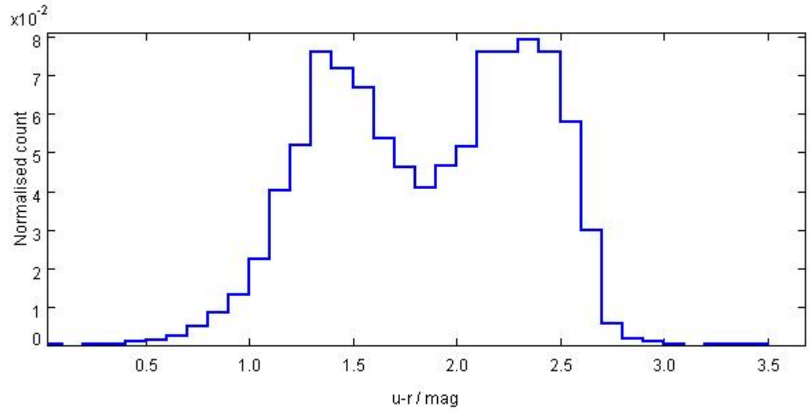

Figure 4.4: *u-r* distribution of optically selected sample indicates similar (comparable) fraction for red and blue population.

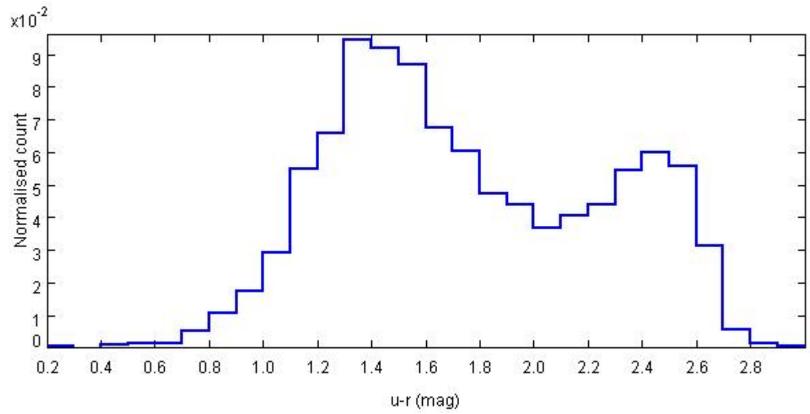

Figure 4.5: *u-r* distribution of UV selected sample indicates a similar kind of behaviour shown by *NUV-r* distribution.

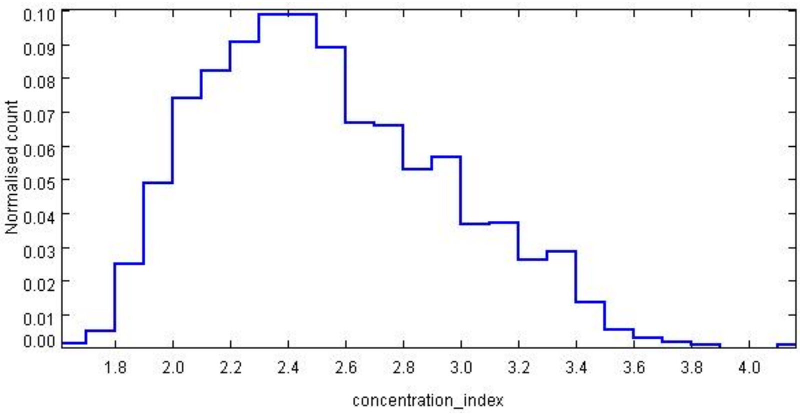

Figure 4.6: Distribution of concentration index (CI) for UV selected sample.

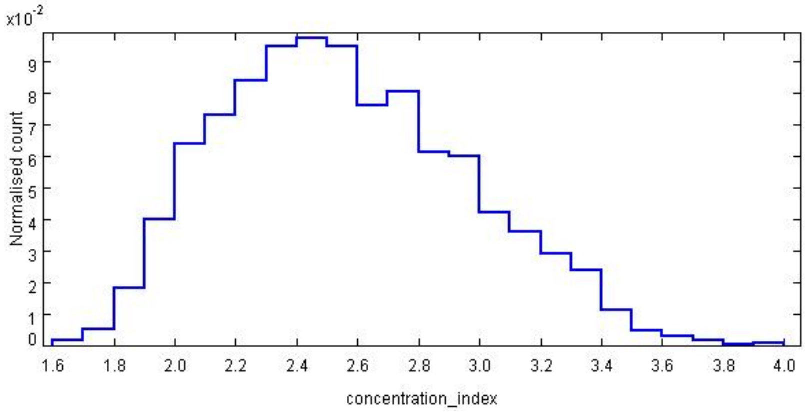

Figure 4.7: Distribution of concentration index (CI) for optically selected sample.

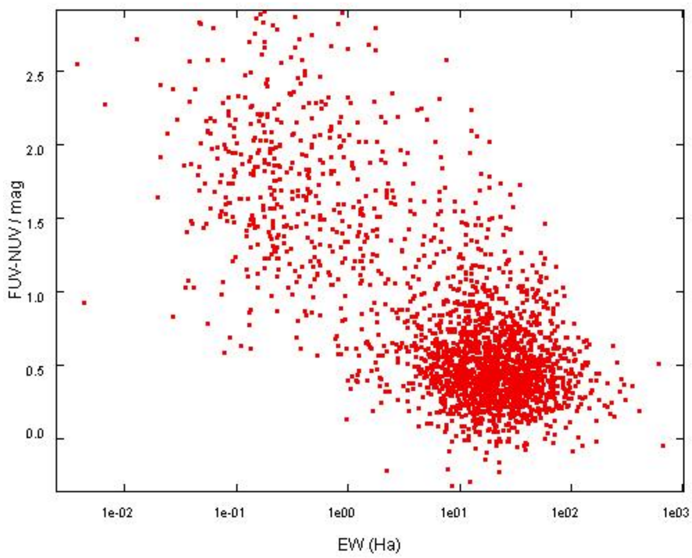

Figure 4.8: Majority of galaxies in UV data found to have significant ongoing SF.

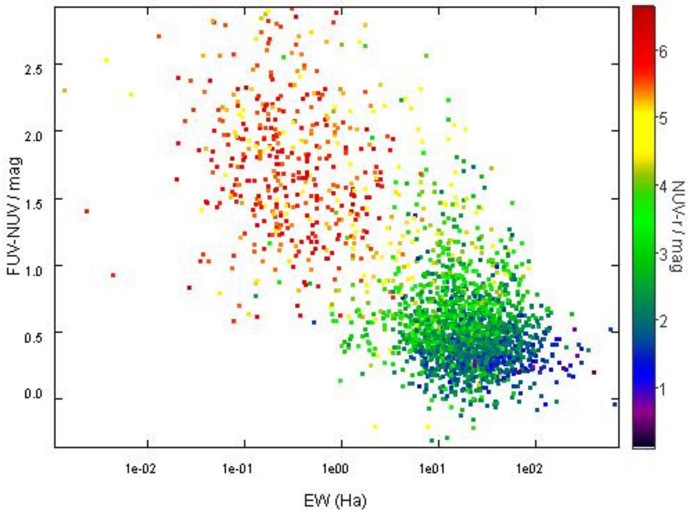

Figure 4.9: Majority of star forming galaxies found to be of blue colour.

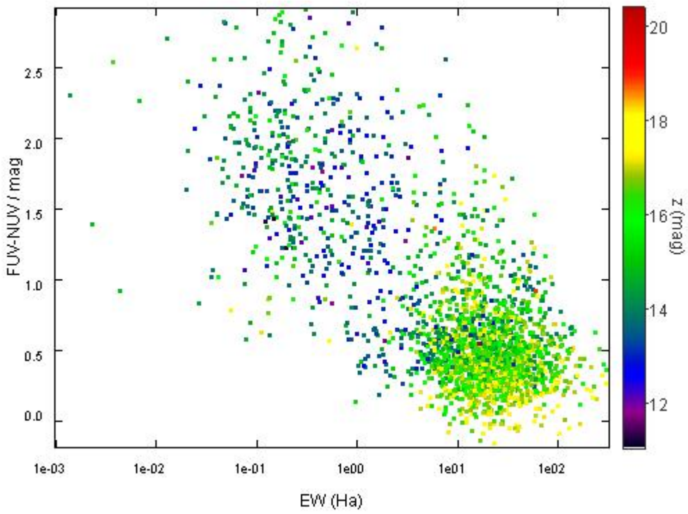

Figure 4.10: Majority of star forming galaxies found to be as dwarfs.

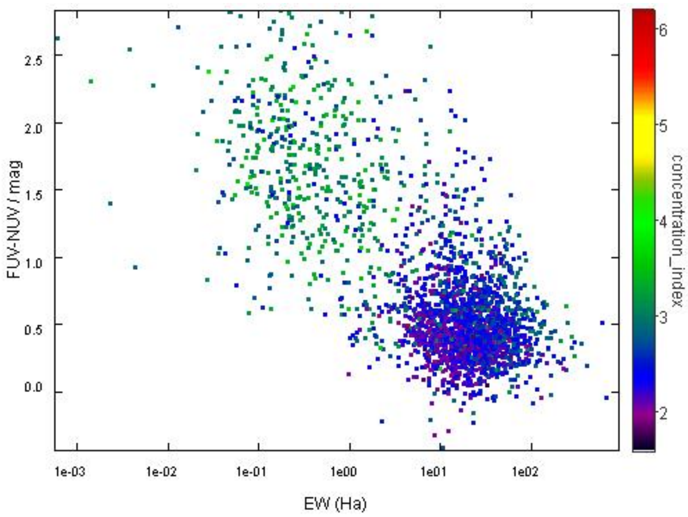

Figure 4.11: Majority of star forming galaxies found to be of spirals and irregulars.

Chapter 5

Analysis II: How galaxy properties vary with the environment?

In chapter 4 we have seen the overall behaviour of galaxies in the Coma supercluster. In this section we particularly look at the behaviour of galaxies in different regions of Coma supercluster and try to quantify the observed environmental dependence by doing KS test. Four environments are defined in Coma supercluster namely 0-0.5r_{200}, 0.5r_{200}-r_{200}, filament and field (discussed in chapter 3).
KolmogorovSmirnov (KS) test is a non-parametric statistical test used to determine whether two samples come from the same distribution. KS statistics measures greatest distance be-tween the empirical distribution function (EDF) of the dataset. The test consider two hypothesis, 1) null hypothesis: two samples follow same distribution. 2) alternate hypothesis:distribution of two samples are different. If the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis and accept the alternative hypothesis. KS test results obtained for different parameters are shown in table 5.4, 5.5, 5.6 and 5.7

5.1 colour

Colour *(NUV-r)* distribution of UV selected galaxies is shown in figure 5.1. Similarly, *u-r* distribution for optically selected galaxies is shown in figure 5.2.

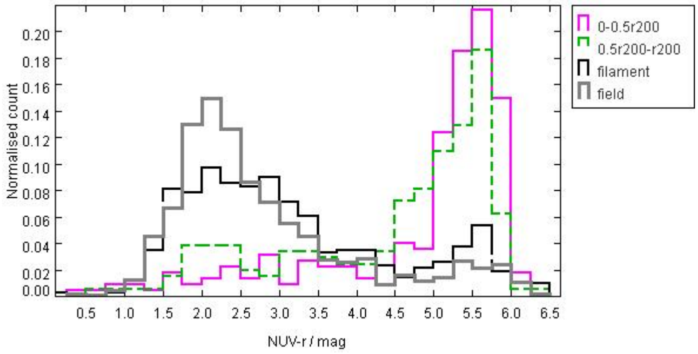

Figure 5.1: *NUV-r* distribution of galaxies. Cluster environment is dominated by red galaxies whereas in filament and field blue galaxies are found in major fraction

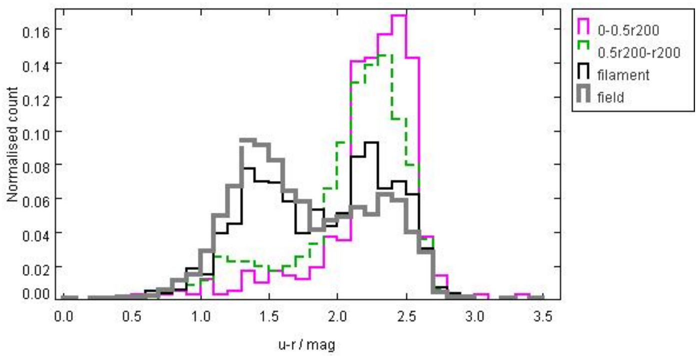

Figure 5.2: *u-r* distribution of galaxies. Cluster environment is dominated by red galaxies . But *u-r* distribution of filament and field itself is bimodal with both blue and red galaxies in comparable fraction.

Both distributions follow similar trend. In both sample set, cluster region is found to be dominated by red galaxies while field and filament is composed of red and blue galaxies. This clearly indicates that bimodality in colour is due to the environment of galaxies they belong to. KS test results obtained for *NUV-r* colour is given in table 5.4

Table 5.1: KS test results for *NUV-r* colour. The statistically significant results are marked in bold.

environment 1	environment 2	p-value (all)	p-value (dwarfs)	p-value (giants)
$0\text{-}0.5r_{200}$	$0.5r_{200}\text{-}r_{200}$	**2.403E-04**	0.608	0.237
	filament	**$\ll 0$**	**6.208E-10**	**$\ll 0$**
	field	**0.000**	**$\ll 0$**	**$\ll 0$**
$0.5r_{200}\text{-}r_{200}$	Filament	**$\ll 0$**	**$\ll 0$**	**2.822E-07**
	Field	**0.000**	**$\ll 0$**	**$\ll 0$**
Filament	Field	**1.578E-08**	**6.358E-05**	**7.159E-03**

KS statistics between NUV-R distribution for 'all' galaxies in each environment imply that type of galaxy population present in each environment is different from one another. Dwarfs and giants in the regions 0-0.5r200 and 0.5r200-r200 seem to be of same type of galaxy population whereas in all other environments it seems to be of different type of galaxy population.

5.2 Mophology

Distribution of CI with respect to different environments is shown in figure 5.3. Fraction of different galaxies present in each environment is given in table 5.3.

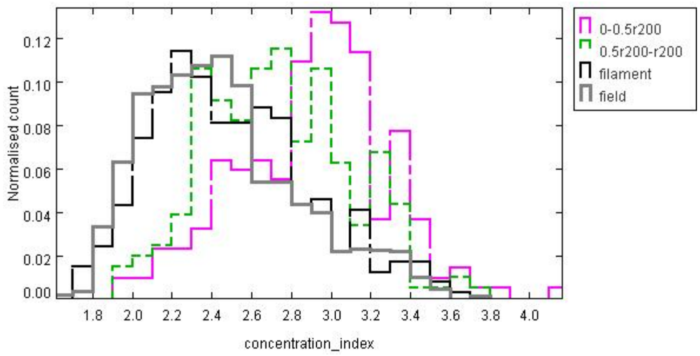

Figure 5.3: Distribution of concentration index (CI) for UV selected sample.

Filament and $0.5r_{200}\text{-}r_{200}$ region seem to have both ellipticals and spiral galaxies in considerable fraction. But the difference between environments is that mean of CI is different for each environment. KS test results for CI parameter is given in table 5.2.

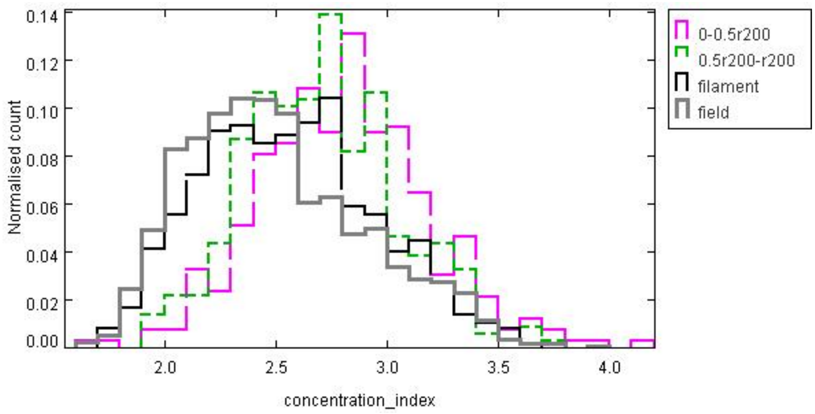

Figure 5.4: Distribution of concentration index (CI) for optically selected sample.

Table 5.2: KS test results for CI (morphology of galaxies). The statistically significant results are marked in bold.

environment 1	environment 2	p-value (all)	p-value (dwarfs)	p-value (giants)
0-0.5r_{200}	0.5r_{200}-r_{200}	**5.197E-07**	0.793	**2.502E-03**
	filament	**$\ll 0$**	**1.244E-05**	**3.723E-08**
	field	**0.000**	**3.513E-08**	**$\ll 0$**
0.5r_{200}-r_{200}	Filament	**6.149E-11**	**1.171E-08**	0.114
	field	**$\ll 0$**	**$\ll 0$**	**2.330E-04**
Filament	Field	**4.320E-03**	0.116	0.184

Galaxies in each environment seem to have different morphology. There can see a similarity in the morphology of dwarfs in the following pair of regions, '0-0.5r200 and 0.5r200-r200'; 'filament and field'. The giants of similar morphology are observed in following regions, '0.5R200-R200, R200-2R200 and filament'; 'filament and field'. In all environments other than the above mentioned ones giants and dwarfs of different morphology are present.

5.3 Mass

Distribution of dwarfs and giants based on z band magnitude is shown in figure 6.3 and their fraction in each environments is given in table 5.4. Cluster core (0-0.5r_{200}) is dominated by giants whereas low density regions such as filament and field is dominated by dwarfs. In 0.5r_{200}-r_{200} region dwarfs and giants are found in comparable fraction. This indicates that

environments	fraction of spirals and irregulars (%)	fraction of ellipticals and lenticulars (%)
0-0.5r_{200}	22	78
0.5r_{200}-r_{200}	38	62
filament	63	37
field	72	28

Table 5.4: morphology of galaxies in different environments.

the region 0.5r_{200}-r_{200} plays a role in change of mass.

environments	fraction of dwarfs (%)	fraction of giants (%)
0-0.5r_{200}	31	54
0.5r_{200}-r_{200}	48	41
filament	67	33
field	71	29

Table 5.3: Dwarf and giant galaxies in different environments.

5.4 Star formation

We looked at the star forming activity of galaxies (shown in fig 5.4, 5.5, 5.6 & 5.7) in each environment by checking the correlation between *FUV-NUV* and EW (Hα). Galaxies with significant recent SF (low FUV-NUV) found to have ongoing SF. Galaxies with little or no SF activity found to have high *FUV-NUV* colour, an implication of declining SF activity with time.

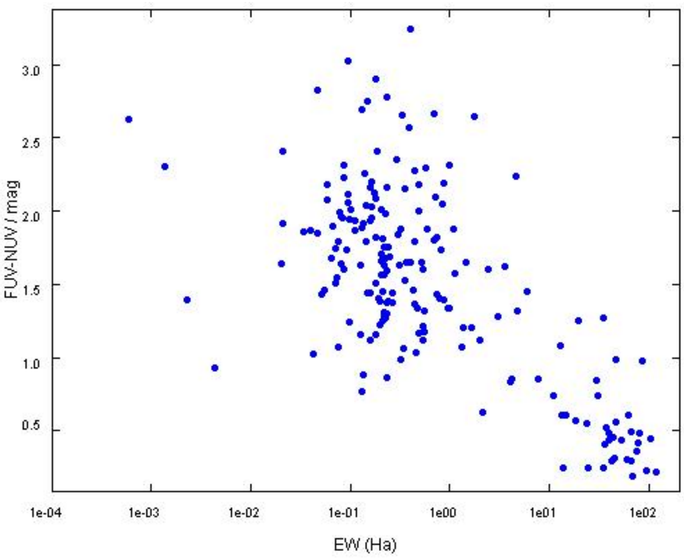

Figure 5.5: Cluster core seems to be dominated by galaxies with little or no SF activity.

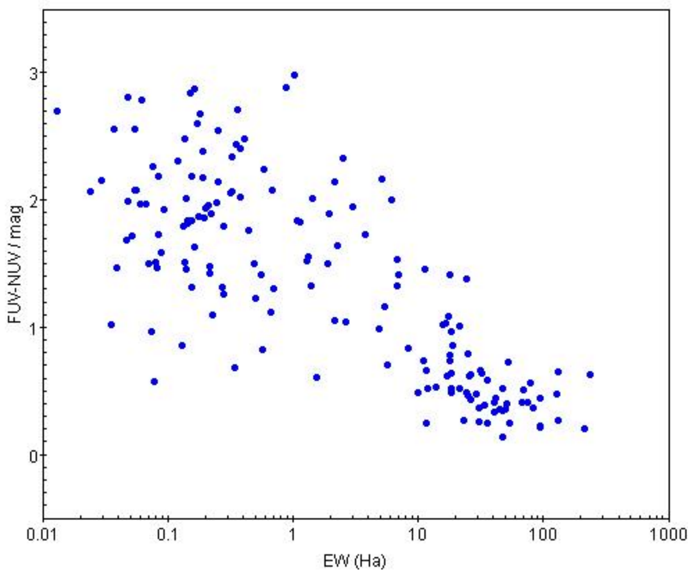

Figure 5.6: Fraction of star forming increases beyond the cluster core.

Majority of galaxies in cluster region have low SF activity. Moving outward from cluster core, fraction of SF EW (Hα) >4 galaxies increases. Major fraction of galaxies in both filament and field regions are actively star forming ones.

Then we estimated the fraction of star forming galaxies present in each environment from their EW (Hα) values and is given in table 5.5 We expected the declination/suppression of SF activity towards cluster core (0-0.5r_{200}). But we saw that majority of star forming galaxies with no SF is found in 0.5r_{200}-r_{200} which indicates that the region 0.5r_{200}-r_{200} has a greater role in suppressing SF activity. Also fraction of galaxies with a little SF activity ($0 < \text{EW (H}\alpha) < 4$) seems to increase towards center.

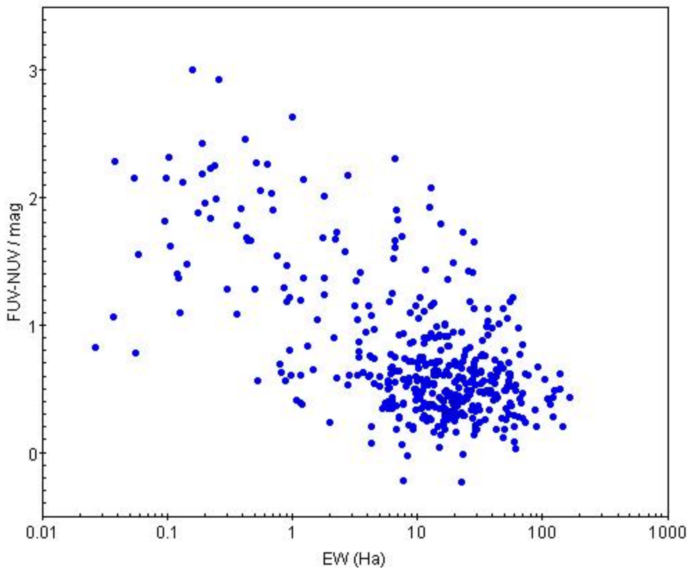

Figure 5.7: Major fraction of galaxies are actively star forming ones.

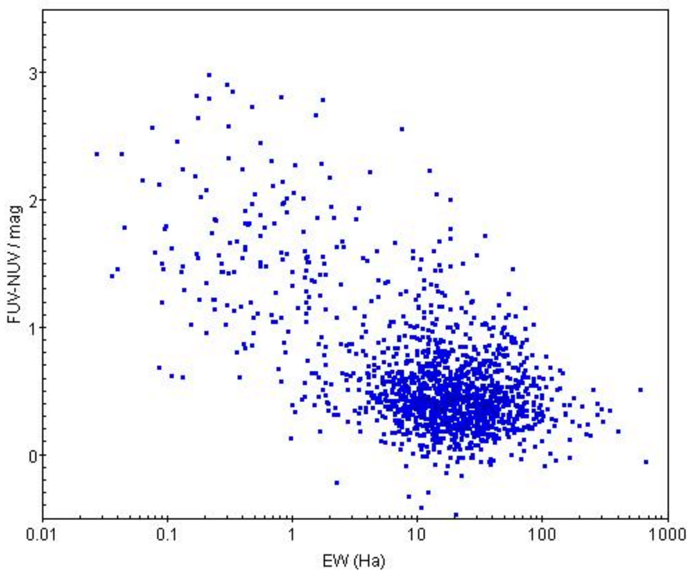

Figure 5.8: Major fraction of galaxies are actively star forming ones.

environments	$0 < EW$ (Hα) < 4 (%)	EW (Hα) > 4 (%)
0-0.5r_{200}	67	18
0.5r_{200}-r_{200}	47	33
r_{200}-2r_{200}	31	58
filament	19	78
field	14	84

Table 5.5: SF activity of galaxies in different environments of Coma supercluster.

Table 5.6: KS test results for *FUV-NUV* (recent SF of galaxies). The statistically significant results are marked in bold.

environment 1	environment 2	p-value (all)	p-value (dwarfs)	p-value (giants)
0-0.5r_{200}	0.5r_{200}-r_{200}	**2.505E-02**	0.111	0.610
	Filament	**2.129E-43**	**4.216E-13**	**4.712E-09**
	Field	**0.000**	**3.042E-19**	**8.996E-21**
0.5r_{200}-r_{200}	Filament	**1.027E-26**	**1.795E-14**	**5.037E-07**
	Field	**0.000**	**1.334E-22**	**2.052E-13**
Filament	Field	**7.356E-12**	**1.144E-06**	**1.206E-03**

Table 5.7: KS test results for Hα-EW (current SF of galaxies). The statistically significant results are marked in bold.

environment 1	environment 2	p-value (all)	p-value (dwarfs)	p-value (giants)
0-0.5r_{200}	0.5r_{200}-r_{200}	**8.946E-05**	0.220	0.171
	Filament	**8.408E-45**	**5.878E-09**	**5.657E-14**
	Field	**0.000**	**7.731E-12**	**4.441E-22**
0.5r_{200}-r_{200}	Filament	**5.586E-18**	**8.616E-05**	**1.111E-07**
	Field	**2.013E-28**	**1.008E-06**	**1.773E-10**
Filament	Field	**4.096E-03**	0.156	0.616

From the KS test, we find that galaxy properties change with environment. This is a clear indication that the environment has a role in galaxy evolution. KS test implies that some properties of dwarfs and giants are environment independent. KS test of *FUV-NUV* parameter for dwarfs in filament and field region indicates that their SF activity is different. But the interesting thing is that the current SF activity (EW (Hα)) of dwarfs in these regions found to be similar. KS tests also imply that dwarfs in these region have same morphology, but different colour. Similar behaviour is observed for giants in these regions.Till now, we have seen that colour, morphology, mass and SF of galaxies vary with each environment. Next we checked the correlation between galaxy properties.

How colour and SF correlated at fixed morphology in an environment?

From fig 5.8 we can see that blue star forming ellipticals and red ellipticals with low SF activity are found in considerable fraction. Major fraction of ellipticals in cluster environment are red ones with high *FUV-NUV* colour whereas majority of ellipticals in filament and field region are blue star forming ones. Majority of spiral galaxies found to be blue as well as star forming ones (fig 5.9). Fraction of blue galaxies increases when move outward from cluster core. Filament region is composed of both red and blue galaxies in significant fraction. Field region is composed of both red and blue galaxies. But the contribution from blue galaxies is very high. Field and filament region exhibit similar kind of behaviour, the only difference is in the fraction of galaxies present. Irrespective of environment spiral type galaxies found to be blue and star forming. Ellipticals seem to be of different behaviour in cluster and non-cluster regions. In cluster regions , ellipticals are red with low SF activity whereas in non-cluster region significant fraction of blue ellipticals present.

How colour and SF correlated for dwarfs as well as giants in an environment?

Major fraction of dwarf galaxies belong to all environments are blue star forming ones (fig 5.10). Giants in cluster and non-cluster region shows different behaviour (fig 5.11). Giants in cluster region are red with relatively low SF activity. Giants in non-cluster region are of two types, blue star forming ones and red ones with low star forming which are found in considerable number.

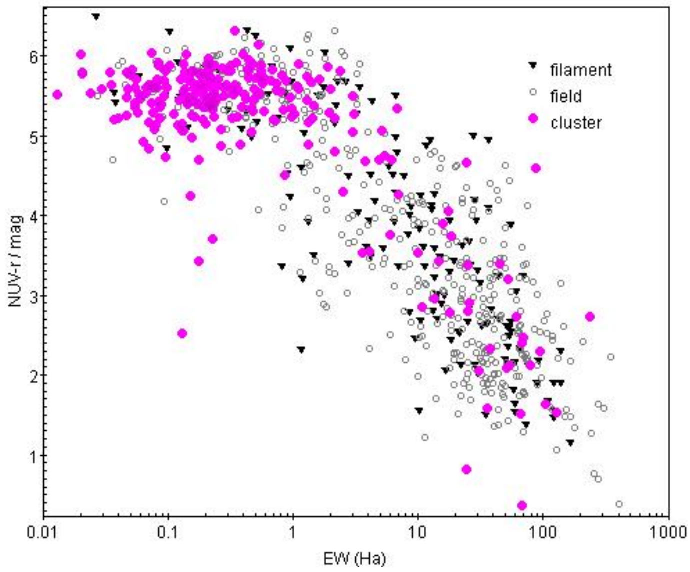

Figure 5.9: correlation between colour and Hα (EW) for ellipticals and lenticulars. Ellipticals seem to be of two types, blue SF ones and red ones with low SF. Cluster environment seems to dominated by red ellipticals and lenticulars with relattively low SF activity. majority of ellipticals in filament and field region are blue star forming ones.

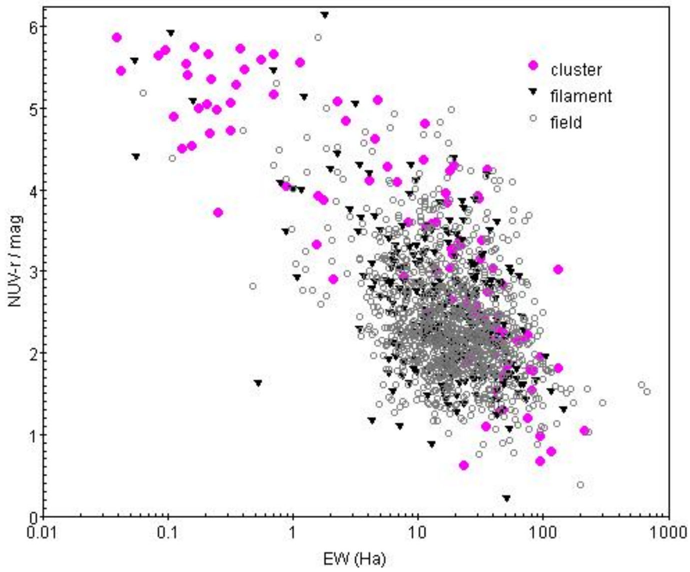

Figure 5.10: correlation between colour and Hα (EW) for spirals and irregulars. Major fraction of spirals and irregulars are blue SF ones. Fraction of red spirals with relatively low SF is very low and they are solely from the cluster region.

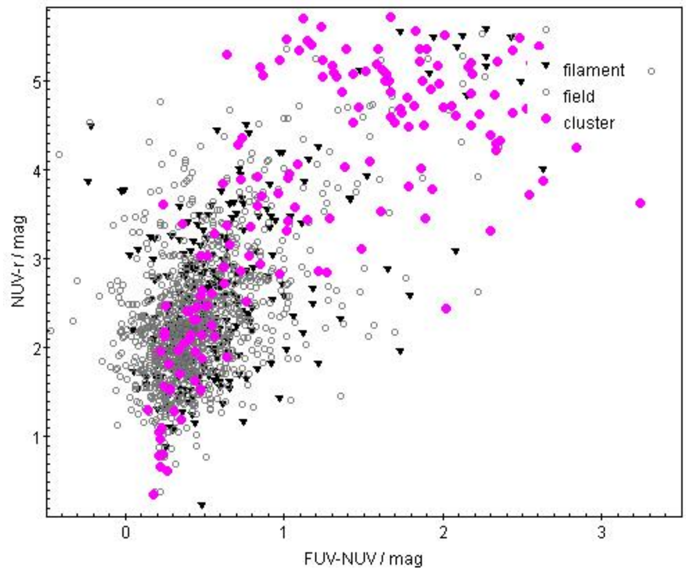

Figure 5.11: correlation between colour and *FUV-NUV* for dwarfs. correlation between colour and Hα (EW) for dwarfs. Major fraction of dwarfs are blue SF ones. The fraction of red dwarfs with low SF is very low and such galaxies are seen to be from cluster region.

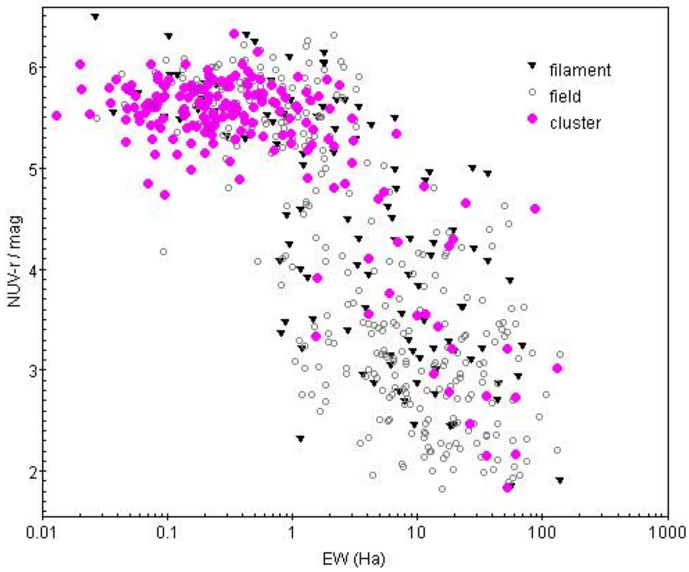

Figure 5.12: correlation between colour and Hα (EW) for giants. Giants are of two types, blue SF ones and the red ones with low SF activity. Cluster region is mainly dominated by red giants with low SF.

Chapter 6

Conclusion

We have partitioned the Coma supercluster into cluster, filament and field and studied the behaviour of star forming galaxies in these environments. We defined the galaxies which have emission in *FUV* and *NUV* bands as the star forming ones.
65% of star forming galaxies are found in sparsely populated field region. Fraction of star forming galaxies in high density cluster region and the filament is only $<$20%.
NUV-r bimodal distribution indicates the existence of 2 types of galaxy population in Coma supercluster. 98% of galaxies are actively forming stars(EW (Hα)$>$4), found to be blue galaxies, i.e. *NUV-r*$<$4.4, which indicates the high correlation between colour and SF activity of galaxies. 79% of star forming galaxies found to be dwarfs. 79% of star forming galaxies found to be of spiral and irregular morphology. Altogether 65% of actively star forming galaxies found to be dwarf spirals with blue colour.
High and low density environments in Coma supercluster are responsible for the observed bimodality in colour. We checked the correlation between colour and SF activity of galaxies in different environments and found that the fraction of actively SF ones (EW (Hα) $>$4) and blue galaxies are comparable irrespective of the environment. The fraction of dwarfs and giants in the region 0.5r_{200}-r_{200} found to be significant and comparable than the cluster, filament and field regions. This suggests that 0.5r_{200}-r_{200} region plays a major role in the observed change of mass from dwarfs in filament and field region to giants in cluster core. 5% of star forming galaxies found to have no ongoing SF (i.e. Hα-EW=0) and we expected that the majority of them reside in cluster core. But it is seen that major fraction of them reside in 0.5r_{200}-r_{200} region, suggesting that 0.5r_{200}-r_{200} region has a role in the suppression of SF activity of galaxies. 0.5r_{200}-r_{200} region and filament found to have both spirals and

ellipticals in significant fraction when compared to high density cluster core and low density field region.

We statistically quantify the observed environmental dependence on galaxy properties by employing KS test. KS test for all galaxies in an environment indicates that colour, morphology and SF activity of galaxies are environment dependant. KS test shows that some properties of dwarfs and giants have no environment dependence. Mainly current SF activity (EW (Hα)) of dwarfs in filament and field regions are found to be similar although their recent SF activity is different. KS tests also imply that dwarfs in these region have same morphology, but different colour. Similar behaviour is observed for giants in these regions. KS test implies that dwarfs in 0-0.5r200 and 0.5r200-r200 regions have similar colour, morphology and SF activity. Except morphology, giants of these regions seem to have similar colour and SF activity. KS test shows that giants have different morphology in cluster and non-cluster region. But giants in filament and field are found to have similar morphology. This indicates the effect of clustering on galaxy morphology. We have taken into account r200-2r200 region as well to check whether the bimodality of colour in filament region is due to r200-2r200 region. Even though r200-2r200 region is removed from filament region, bimodality in colour exists. Hence we conclude that groups belong to the filament might be the reason for the bimodality in colour. KS test implies that giants in the regions r200-2r200 and filament are similar, i.e. they are found to have similar colour, morphology and SF activity. This might be due to the gradual decline in clustering effect beyond the virial radius.

Discussion

Properties of galaxies with no recent SF

We have seen in previous section that major fraction of galaxies which lack an emission in FUV and NUV bands seem to have current SF. One possible reason is *GALEX* has not observations on these galaxies. In this section, we look at how the behaviour of such galaxies vary with environment? Spatial distribution of galaxies with no recent SF is shown in figure 5.16. Majority of them are found in low density environments such as filament and field. Speaking of current SF activity, cluster region found to have little or no SF.

1811 galaxies in optically selected sample have no emission in *FUV* and *NUV* bands as well. We checked their current SF activity ($H\alpha$-EW) and the obtained plots (fig 6.1, 6.2, 6.3, 6.4) and result is shown in table 4.

Major fraction of galaxies that lack *FUV and NUV* emission are passively evolving as indicated by value of EW ($H\alpha$)¡4 and are found mainly in cluster environments.

Table 6.1: SF activity of galaxies that lack *FUV and NUV* emission

$H\alpha$-EW	number of galaxies	fraction
EW = 0	309	17%
0 < EW < 4	725	40%
EW > 4	777	43%

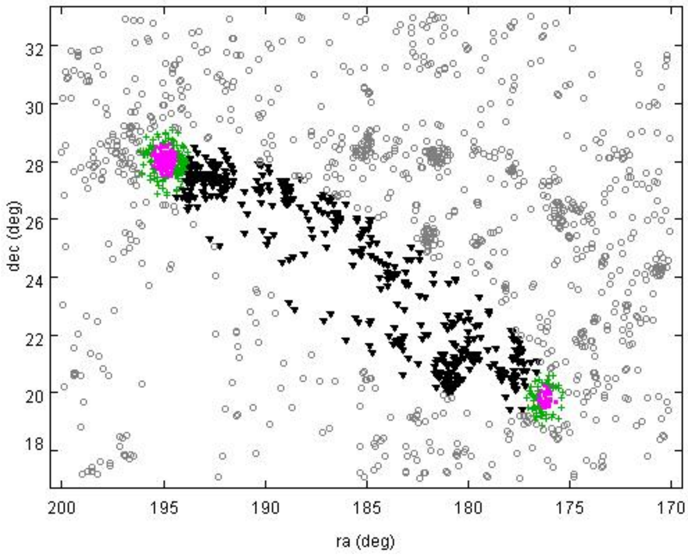

Figure 6.1: Sky plot of galaxies with no recent SF. The closed circles (pink) denotes the 0-0.5r_{200}, cross mark (green) denotes the 0.5r_{200}-r_{200}, triangle (black) denotes the filament region and open circles (grey) denote the field.

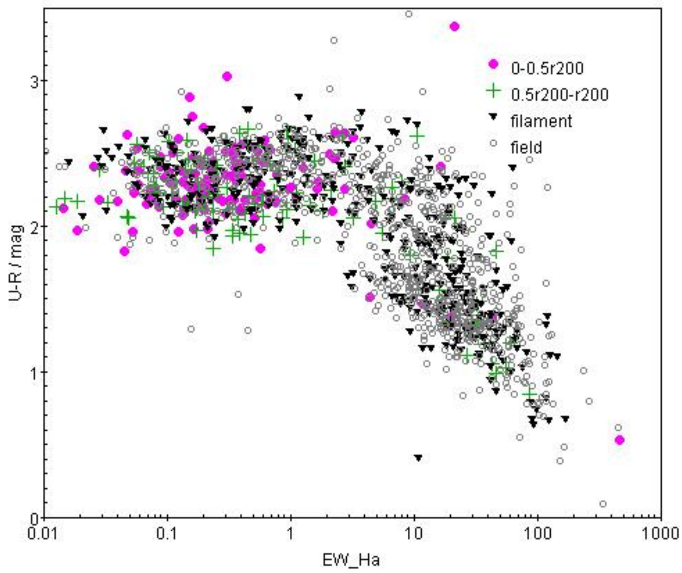

Figure 6.2: correlation between colour and EW (Hα). Both red and blue galaxies are found in comparable fraction. Blue galaxies are mainly found in filament and field region whereas red ones are found in all environments in considerable fraction

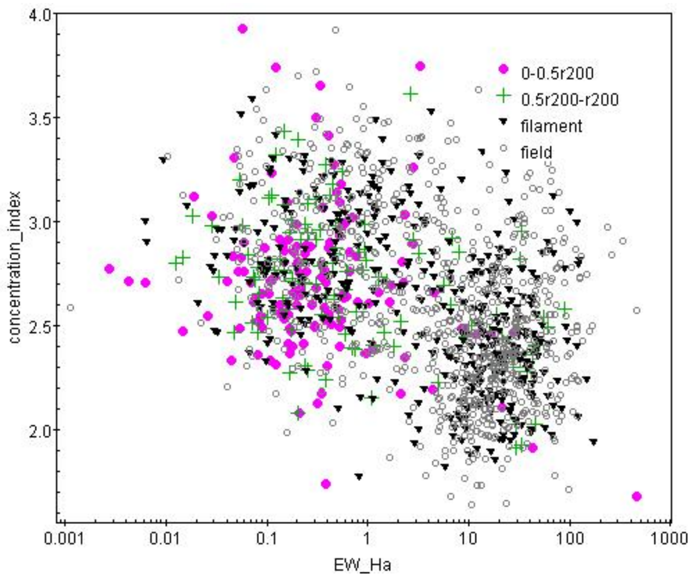

Figure 6.3: correlation between EW(Hα) and CI (morphology). Spirals as well as ellipticals are found in comparable fraction irrespective of environment. But irrespective of morphology galaxies with little or no SF are found in cluster regions.

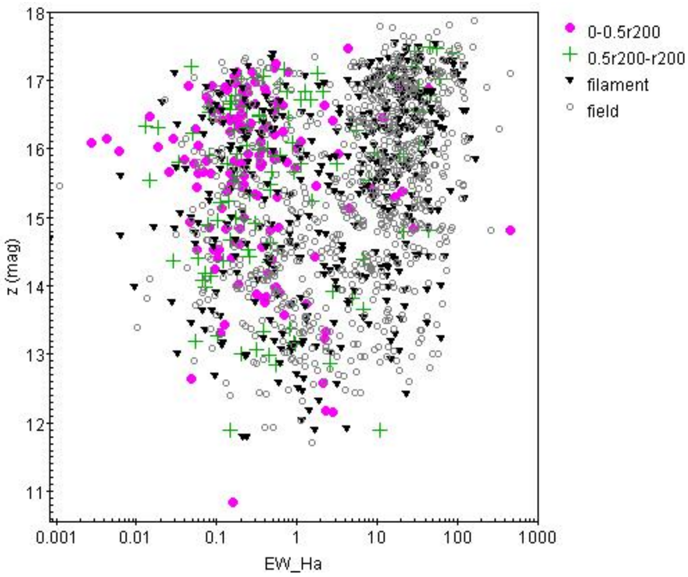

Figure 6.4: correlation between EW (Hα) and z band magnitude (mass). Giants and dwarfs are present in significant fraction. Irrespective of mass galaxies w

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